Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
11 (2007) 998–1007
RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS
www.elsevier.com/locate/rser

Use of different methodologies for thermal load and energy estimations in buildings including meteorological and sociological input parameters

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Received 17 August 2005; accepted 24 August 2005

Abstract

This review paper provides first an overview of the background for meteorological and sociological influences on thermal load and energy estimations. The different yearly representations of weather parameters (test reference year (TRY), design reference year (DRY), typical meteorological year (TMY) and weather year for energy calculations (WYEC)) are discussed, and compared to simplified representations of weather characteristics. Sociological influences on energy demand are discussed in relation to attitude and culture.

Many methods exist for estimating thermal load and energy consumption in buildings, and they are primarily based on three different methodologies; regression analyses, energy simulation programs and intelligent computer systems. Regression analyses are mainly based on large amounts of metered load data, long-term weather characteristics and some information about the buildings. Energy simulation programs require detailed information about the buildings and sociological parameters, as well as thorough representation of weather data. Intelligent computer systems require metered load data, weather parameters and building information. The advantages and disadvantages of the alternative methodologies are discussed, as well as when and where to use them. Finally, the more specific usages of the methodologies are exemplified through three specific methods: conditional demand analysis (CDA), engineering method (EM) and neural networks (NN).

Keywords: Energy planning; Methodologies; Load estimations; Regression analyses; Energy simulation; Intelligent computer systems

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2005.08.005

Contents

1. Introduction

Energy planning is a complex task that includes many uncertainties such as available energy resources and energy carriers, distribution systems, peak load values, load profiles and total energy demand. Load and energy demand may be estimated using many different methods. The problem is, which method should the energy planner choose for his or her estimates of the maximum load, load profile and total energy demand for the area in question? Energy planners need this information to be able to project an economically, technologically and environmentally optimal energy system in terms of design and operation [1].

The maximum load value indicates the load level that the energy production unit has to fulfill, and the load level also helps to establish what kind of existing technology can meet that requirement. The running costs and the environmental impact of the energy system are dependent on the operation of the system. The load profile for the specific area will give an indication of the system's behavior throughout the year and will also show the optimal operation of the energy system. It is important to estimate the total energy demand in terms of the possible exploitation of available energy resources in the surrounding area.

The following textbox specifies the difference between the methodology concept and the method concept used in this review article:

> *Methodology*—the fundamental background for the different methods.
> *Methods*—the different estimation techniques developed for load and energy estimations.

This review paper first provides an overview of the background for the meteorological and sociological influences on thermal load and energy estimations. The most common methodologies that have been developed for such estimations are then described, with a discussion on the advantages and disadvantages of the alternative methodologies, as well as when and where to use them.

Load and energy estimations in buildings are primarily based on three methodologies: regression analyses, simulation programs and intelligent computer systems. Different methods are developed based on these foundations to fulfill the energy planner's requirements for an accommodated estimation tool. Load and energy estimation tools have different requirements in terms of input data as well as various applicabilities. All of the methods evaluated need weather data, and methods that are not primarily based on metered energy data also need sociological data.

2. Weather files and sociological factors in load and energy estimations

Energy planning, particularly load and energy forecasting, require a great amount of background information. This information includes customer type, size of the building, control and maintenance of the energy system and the allocation of different end uses, i.e. space heating, cooling, electrical equipments, domestic hot water and more. However, some of the most important factors that influence the load and energy demand are climatic parameters as well as consumer behavior.

2.1. *Different representation of climatic parameters*

Different climatic parameters influence the load and energy demand such as temperature level vs. space heating, ventilation and cooling; wind speed and direction vs. space heating and ventilation; solar irradiance vs. cooling and lighting; hours of daylight vs. lighting and cloud layer vs. space heating. The climate changes from place to place as well as on a yearly basis, making the generation of a common representation of the normal climate into a challenging task at any given location.

The representation of weather data can be divided into yearly weather files and simplified weather files. The most important yearly representations are test reference year (TRY), design reference year (DRY), typical meteorological year (TMY) and weather year for energy calculations (WYEC) [2,3].

TRY consists of 1 yr of actual weather data chosen from the available annual weather years recorded. The specific year is chosen based on certain criteria. Years that include months with extremely low or high mean daily temperatures are eliminated. This process is continued until 1 yr remains, and this year represents the TRY. TRY is not sufficiently accurate and, therefore, it cannot be used in energy requirements calculations exceeding several years. TRY may be applied when comparing the different designs in retrofit options [2].

A DRY is a further development of the TRY. DRY consists of 8760 sets of hourly weather data—number of hours that constitutes a normal year—for a given location. The latter year is mostly used for annual energy simulations where the computer programs can handle more than one climatic parameter. DRY includes hourly climatic parameters such as global, diffuse and direct normal irradiance, dry bulb and dew point temperature, cloud information, wind speed and direction. Like TRY, DRY is compiled from metered data at

a certain location during a 12 month period. Twelve representative months are selected and adjusted giving each month a true mean value along with the variance for the main climatic parameters [3].

TMY, on the other hand, represents a constructed weather data year based on actual meteorological data. Each month consists of typical or average months from annual metered data over several years. The months selected approximate the long-term average conditions. Therefore, TMY is a compilation of 12 months that might have occurred in different years. Consequently, two adjacent months may have a "jump" in weather conditions in the transitional period. This data is smoothed using a curve-fitting technique [2].

The last yearly weather representation is called WYEC. This weather data file is constructed using months that show the closest proximity to the 30-year normal, where both temperature and solar radiation are taken into consideration. Some days and hours are replaced by corresponding data from the same month, but from a different year, to bring the weather file closer to the published 30-year normal for that month [2]. This representation is mainly used in long-term load and energy predictions due to the similarity to the 30-year normal.

Yearly representations of weather parameters require a large amount of data. The accuracy level of the climatic representation must correlate with the load and energy estimation method used by the energy planner. For example, a large amount of weather data will increase the simulation time. A possibility for reducing the simulation time might be to use simplified weather data and a corresponding method.

Westphal and Lamberts [4] present a simplified weather file with 21, 14 or only 7 days per month of data. In a case study they carried out in Brazil, they found that the difference in energy estimation between simulations using TRY and the simplified weather data file was as high as 18%. The simulation time using the simplified data was reduced as much as 50%. The simplified weather data file gave satisfactory results for buildings with low thermal mass, but the methodology presented in Westphal and Lamberts [4] revealed weaknesses when the simulation involved buildings with high thermal mass. The main weakness is that the simplified method did not take into account the influence of thermal inertia in buildings with a large thermal mass.

In some cases it is also possible to use simplified weather data such as a design day. Chou et al. [5] present a methodology for the selection of a design day weather file for energy simulations based on TMY. The selected design day is not based on the most adverse set of weather conditions, but rather on weather conditions that give a low peak, as well as few hours of load not met. Simplified weather data offers the advantage of allowing the use of less complex simulation programs. The disadvantage lies in the accuracy of the output from the corresponding simulation program.

Table 1 presents the different climatic representations introduced in Section 2.1.

The use of some of the different weather representations will be discussed in relation to the presentation of the methodologies for load and energy estimation in Section 3.

2.2. *Influence of sociological factors*

The amount of energy consumed is very dependent upon the attitude and awareness of the energy customers. The consumption pattern in different building types, like households, schools and office buildings, is unique for that particular building. Therefore,

Table 1
Overview of different climatic representations introduced in Section 2.1

Yearly representation	Test reference year (TRY) Design reference year (DRY) Typical meteorological year (TMY) Weather year for energy calculations (WYEC)
Simplified representation	Simplified weather file Design day

customer influence differs depending on what kind of buildings they spend their time in. Consumers will have less influence in a building with automatic control than they will have in a manually controlled building. Awareness and attitudes towards energy consumption are more evident in household consumption than in situations where many people may simultaneously have an influence on energy use, such as in office buildings.

Aune [6] has performed several field surveys and in-depth interviews with several people in different Norwegian households in order to characterize different consumer groups. She has learned that attitude and consumption do not necessarily coincide, and that the way the consumers think they use energy might not be reflected in the actual consumption.

The actual energy consumption also depends upon the culture. Wilhite et al. [7] have learned that the Norwegian energy culture is intensive in relation to space heating and lighting, while the Japanese people use less energy for space heating and lighting. Therefore, this results in a higher energy bill for Norwegian households in terms of space heating and lighting consumption. The Japanese, on the other hand, have a very energy intensive and extremely important bathing culture, which means that domestic hot water use accounts for a large part of their energy bill. Differences in culture, attitudes and building practices are important, and should be considered when estimating loads and energy consumption. Some methods, like the energy-signature method [8], take this into consideration, while some building simulation programs concentrate mainly on the building's physical behavior. According to Richalet et al. [9], a methodology for load and energy estimations should be based on measured energy data, because the real behavior of the building can differ significantly from its design due to the operation of the building's energy system.

3. Different methodologies for load and energy estimations

Computers and computational expansion over the last 40 yr have led to the rapid evolution and improvement of calculation methods for load and energy estimation [10]. This section presents an investigation of the different methodologies being applied today, with descriptions of selected methods.

The meteorological and sociological factors described in Section 2 will be discussed later in this section in relation to the impact the different factors have on load and energy estimations.

3.1. Overview of the methodologies

Based on an analysis of selected articles involving load and energy estimations, load and energy estimations can be described as primarily based on three methodologies: statistical approaches/regression analyses, energy simulation programs and intelligent computer systems.

3.1.1. Statistical approaches/regression analyses

A statistical approach to load and energy predictions is based on large amounts of hourly metered energy consumption data. The probability sample must have a high level of statistical significance in order to meet the accuracy requirements of the stakeholder/energy planner.

Load and energy predictions are mainly based on linear or multivariate regression analyses. A regression analysis expresses the mathematical correlation between different factors, if a correlation in fact is present. This analysis also gives an indication of the quality of the correlation between various energy consumption measures, and climatic parameters such as load and outdoor temperature [11].

The representations of climatic as well as sociological parameters are very important in terms of regression analyses. Consumer behavior is more or less reflected in the hourly metered energy data, but the weather data should be presented as a yearly representation of climate at the specific location.

Examples of load and energy estimation methods based on statistical methodology and regression analyses are USELOAD [12], computational demand analysis (CDA) [13,14], the Finnish load model [15] and energy-signature [8].

3.1.2. Energy simulation programs

Simulation programs are "…an attempt to emulate the reality" [10]. Consequently, energy simulations in buildings require a large amount of data, both precise weather parameters and detailed description of the buildings. Simulation programs mainly model the energy conservation in the buildings including transmission, ventilation and infiltration losses. In addition, the model must factor in domestic hot water consumption as well as lighting, electrical equipments and internal heat gains [10].

Energy simulation programs are mainly based on two different modeling techniques: a response function method (analytical method) or numerical methods. The response function method solves linear differential equations that include time invariant parameters, while numerical methods handle nonlinear, time varying equation systems. Even though programs based on the response function method are often easier to validate, the numerical methods are preferred because they can solve the equations simultaneously, handle complex flow path interactions and accommodate time varying system parameters [10].

The primary numerical method is a nodal network representation of the building. This means that the whole building, or one specific room, is divided into segments where each segment is represented by one node. Energy conservation equations are developed for each node, and the entire nodal network is solved simultaneously. Many simulation programs are based on the nodal network model, but the differences lie in the solution techniques [10].

Examples of load and energy simulation programs based on nodal networks are ESP-r [10], EnergyPlus [16] and engineering method (EM) [13].

3.1.3. Intelligent computer systems

The last methodology for load and energy estimations presented in this review article is called intelligent computer systems, or artificial intelligence, and the systems consist of expert systems and artificial neural networks. Both computer systems go beyond straightforward programming. Expert systems "make decisions" based on an interpretation of data and a selection among alternatives. Neural networks (NNs) are trained in relation to a set of data until the network recognizes the patterns presented. The artificial NN may then make predictions based on new patterns [17].

The latter system is the most suited for load and energy estimations because it is able to handle incomplete data which might result from metered energy data and some climatic parameters. NNs can also solve nonlinear problems as well as "…exhibit robustness and fault tolerance" [17].

An example of a load and energy estimation method based on intelligent computer systems is presented by Aydinalp et al. [13] concerning the prediction of energy demand in Canadian households. They call the method NN.

3.2. Comparison of the different methodologies

The methodologies presented differ in many ways in terms of what kind of input data they require, and when and where to use them. This section provides a short discussion of the input data, with a special emphasis on meteorological representations as well as a discussion of when and where to use the different methodologies.

The amount of input data required by the methodologies differs according to the accuracy level of the calculations. A regression analysis primarily needs load meterings, weather characteristics and some background information on the metered buildings [12,14]. Simulation programs, on the other hand, do not need load meterings, but weather characteristics and detailed information on the buildings are extremely important. The latter methodology also requires information about the behavior of the consumers, i.e. sociological parameters [10]. Intelligent computer systems process metered load data, weather characteristics, sociological parameters and background information of the buildings. The more accurate information provided to the intelligent computer system, the better results the solution algorithm will give [17]. This is also true for regression analyses and simulation programs, because rubbish in equals rubbish out.

All three methodologies can provide both short-term and long-term predictions for load and energy demand depending on the accuracy of the input parameters. Long-term predictions are the most interesting from the energy planner's point of view. The uncertainty factor concerning the input parameters is distinctive in terms of the climatic representation. The yearly representations of weather parameters discussed in Section 2.1 are most interesting in relation to simulation programs and intelligent computer systems, but yearly representations are also used in regression analyses. TRY is most suitable for short-term predictions of load and energy demand because of its real representation of weather characteristics. DRY has manipulated real data and may be used in both short-term and long-term predictions. TMY and WYEC consist of constructed data representing

long-term average climatic parameters. As a consequence, TMY and WYEC are most suited for long-term load and energy predictions [2,3].

The methodologies presented are further developed into more specific load and energy estimation tools, but the applicability is based on the program foundation. Regression analyses are primarily used in load and energy estimations involving several customers, i.e. energy planning for a specific development area where there are many end-users [15]. Because of the detailed nature of simulation programs, the application of this load and energy estimation tool is used with one or just a few large customers. Simulation programs are, therefore, mostly used in retrofitting of already existing buildings [10]. The application of intelligent computer systems are somewhere in between regression analyses and simulation programs [13].

3.3. Exemplification of methods for energy and load estimations

A summary of the specific methods developed for load and energy estimations presented in Section 3.1 is listed in Table 2 in relation to the methodology they are based on.

The different methodologies will be exemplified through CDA, EM and NN.

3.3.1. CDA

CDA is based on a regression method, and the regression level is on the end-use and not the total energy demand [13]. The different appliances (electrical equipment, cooling and heating devices) at the customer level are summed up to estimate the total energy demand for that particular customer. Energy consumption, electrical appliances, demographic features, energy market prices and weather data are necessary when applying the CDA method. The method alone is relatively inexpensive and this results in less precise estimates for the different end uses [14].

3.3.2. EM

EM is presented in an article by Aydinalp et al. [13], and the method is based on the development of a database for the residential sector in Canada. The database is representative for the national housing stock concerning energy demand. The energy demand for the houses in the database is estimated using a simulation program. Detailed descriptions of the houses in the database are necessary. The advantage of using this

Table 2
Overview of different methodologies and corresponding methods for load and energy estimations

Methodology	Method
Statistical approach/regression analyses	Energy-signature *Conditional demand analysis—CDA* Finnish load model USELOAD
Energy simulation programs	*Engineering method–EM* ESP-r EnergyPlus
Intelligent computer systems	*Neural networks– NN*

method is EM's ability to evaluate different energy efficiency upgrade scenarios. The simulation program requires weather data files representing long-term averages.

3.3.3. NN

The third method introduced in Section 3.1 is the NN method. This is an information-processing method inspired by the way the human brain processes information. NNs "...are considered to be intuitive because they learn by example rather than by following programmed rules" [13]. Other advantage of using NNs is that they can handle noise and incomplete data, and they can perform predictions at high speed [17]. This method also requires weather characteristics including heating and cooling degree days as well as other climatic parameters [13].

3.3.4. Comparison of the different methods

The different methods have different capabilities, but each of them can be used in load and energy demand modeling for different customers. EM is the most detailed and flexible model and, consequently, this model requires detailed data and engineering expertise to be developed. The CDA-based model, on the other hand, does not require as detailed data, but the number of buildings in the database has to be large because of the regression analysis. The model cannot provide as much detailed information and flexibility as EM. The NN method is still at the development stage, but this approach is very promising in terms of energy demand modeling. The NN model is situated somewhere between EM and CDA in terms of development and use [13].

4. Conclusion

Many methods exist for making load and energy estimations, but they are all primarily founded on three different methodologies. The first methodology, regression analysis, is mainly based on large amounts of metered load data, long-term weather characteristics and some information about the buildings being modeled. A statistical approach is most suitable for large development areas and long-term estimates of the expected load and energy demand. The second methodology, an energy simulation program, requires detailed information about the buildings and sociological parameters, as well as a thorough representation of weather data, i.e. weather representations like DRY or TMY. Simulation programs are founded on the transfer function method or the numerical method. The latter method is the most widespread, and this approach is suitable for short- or long-term load and energy simulations in one or a few buildings. The third and last methodology, intelligent computer systems, is primarily based on neural networks that process information based on the way the human brain function. Intelligent computer systems require metered load data, weather parameters and building information. Based on this information, the neural network is trained until the pattern in the dataset is revealed. Neural networks may be used for both short- and long-term predictions of load and energy, and this approach is proper for one building or several buildings.

Acknowledgement

I would like to thank Nancy Bazilchuk for all her help and constructive feedback.

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